Fusion Theory: Issues, Highlights and Future Needs

Presented on behalf of the

Theory Coordinating Committee

http://web.gat.com/theory/tcc/

By Vincent Chan

DOE Budget Planning Meeting

Gaithersburg, MD, March 18-19, 2003

TCC Statement of Purpose

The purpose of the Theory Coordinating Committee is to bring to the US controlled fusion program the best insights and results of theoretical physics. To this end the committee attempts to identify fusion physics issues that would particularly benefit from theoretical study, and to inform the theoretical community about them. It also investigates administrative developments that might affect theoretical fusion research. Finally, when the committee concludes that fusion program policy could take better advantage of theoretical effort and talent, it attempts to influence that policy.

(adopted 1993)

Excerpts of TCC Letter to Dr. Jill Dahlburg, Chair FESAC Sub-Panel on Integrated Simulation and Optimization of Fusion Systems (May 6, 2002)

The TCC feels strongly that

- The initiative must advance the level of the physics contributing to the integrated model as well as developing the integration
- The initiative must foster and be open to incorporation of good new ideas that develop during the course of its life

TCC recommends that the initiative includes 3 components

- The mainline integrated simulation
- Improved models of constituent processes or sub-systems
- Exploratory research on novel algorithms and innovative approaches

IT WILL NEED SIGNIFICANT NEW FUNDING TO LAUNCH A PROJECT OF THIS MAGNITUDE

TCC Discussion on OFES Pilot Topical Computing Facilities

Two pilot topical computing facilities have been initiated by OFES in the past year

Objectives of the PPPL facility are:

- **Investigation of ways to impact capability and capacity computing through optimization of commodity-based clusters**
- **Grid computing experimentation across homogeneous platform and evaluation of high-speed processor communication**
- **Exploration of new architecture for key applications**

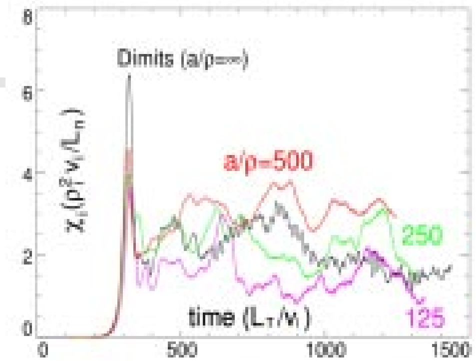
Objective of ORNL facility is:

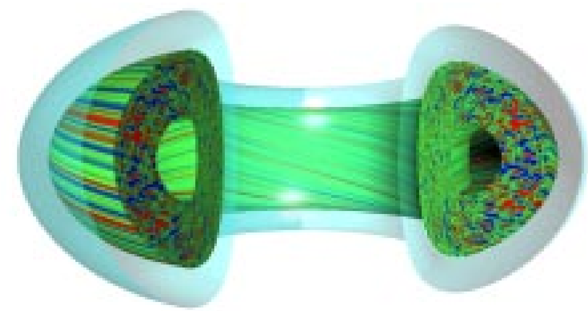
- **Demonstration of much higher efficiency (achieved flops to processor rate) by a combination of hardware architecture and algorithm improvements**

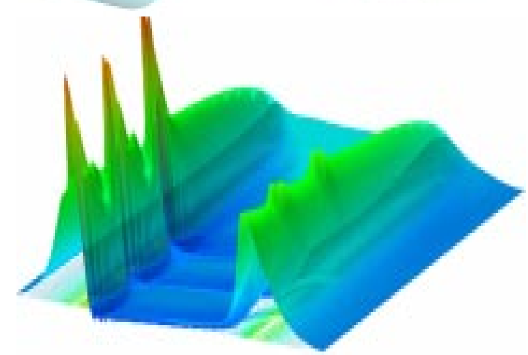
TCC notes that while development of capability computing is clearly needed, the total cycles per year (capacity) available for applications is an important measure that affects productivity. The costs of human time and hardware are equally important

Investment in Theory and Computing has Significantly Advanced the Fidelity of Simulation and Modeling Codes

- **Nonlinear results from global gyrokinetic PIC code (GTC) benchmarked against local (flux-tube) simulation in gyro-Bohm regime**
  - **Linear growth rates agree with Cyclone case results**
  - **Made contact with analytic theories on zonal flow**
- **Global gyrokinetic continuum code (GYRO) now includes essential physics**
  - **Kinetic ions and electrons at finite beta***
  - **General geometry with profile variation and self-consistent ExB**
- **MHD code (M3D) capable of simulating nonlinear evolution of toka equilibrium with zero current density**
  - **Zero current on axis observed even with attempted current drive**
  - **n=0 reconnection responsible for flattening current profile**



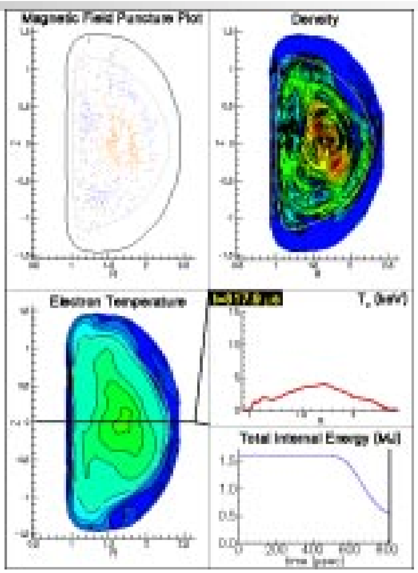


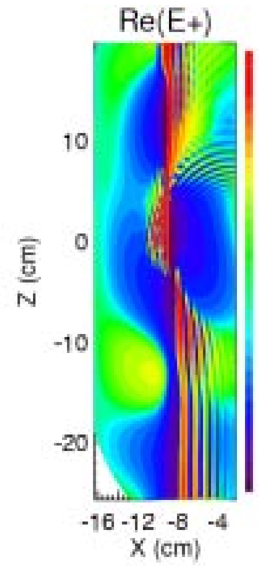


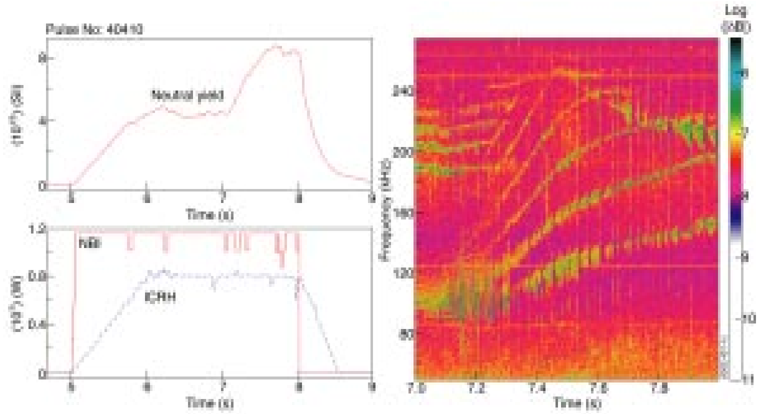
*** Flux-tube codes (SUMMIT & GS2) also have these features**

Comparison Between Theory and Experiment in Tokamaks has reached a Sophisticated Level

- Nonlinear MHD simulation (NIMROD) has successfully reproduced an experimental discharge undergoing a high-beta disruption
  - S and $\kappa_{//}/\kappa_{\perp}$ values approaching experiment
  - Timescale of unstable mode growth agrees with theory
- Improved resolution of a full-wave ICRF code (TORIC) has allowed mode converted IBW and ICW to be resolved
  - Identified PCI measurement on Alcator C-Mod as ICW
- Alfven eigenmode theory generalized to RS tokamak plasmas to interpret "cascades" observed on JET and JT-60U
  - Cascades routinely used as a q-profile diagnostic for ITB's
- Physics based core transport models are widely used in integrated modeling codes
  - Profiles predicted by GLF23 and Multi-Mode compared with experimental data
  - GS2 calculations applied to understand ITB formation and control
- Poloidally localized neutral fueling predicted and observed to influence toroidal flow shear on MAST



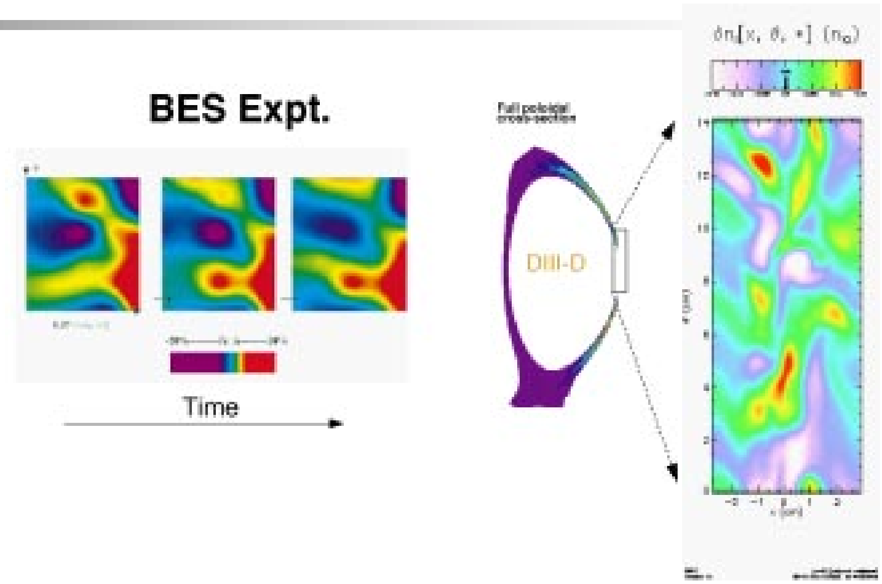




The Plasma Edge and Pedestal has Significant Influence on the Overall Tokamak Performance but Theoretical Understanding is Substantially Behind that of the Core

Edge influences:

- Fueling, power losses, and impurities
- L-H transition
- Density limit
- Core confinement
- Large scale edge fluctuations



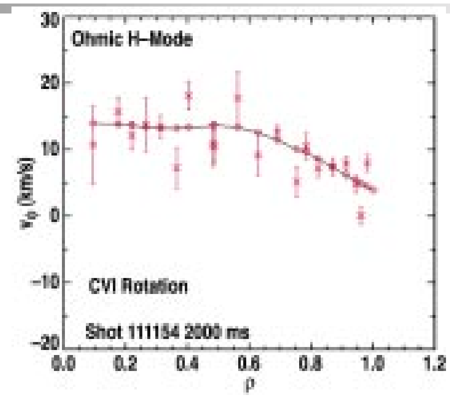
Edge and pedestal theory needs - smooth edge to core matching required

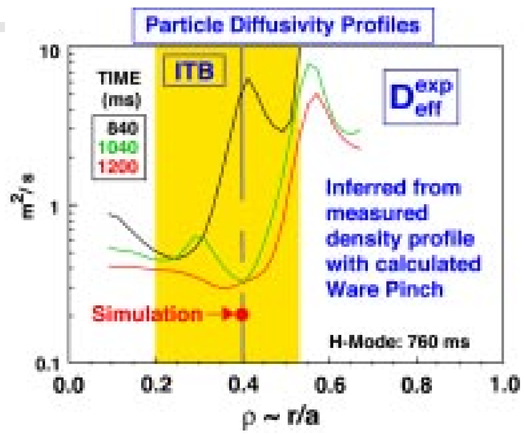
- Continue to improve exisiting 2-D and 3-D fluid edge codes (BOUT)
- Extend core codes toward higher collisionality and gradient scales
- Develop (gyro-)fluid code spanning short to long MFP
- Begin formulating a kinetic scheme for SOL, pedestal and core

Unique features of edge make theory and modeling challenging

- Steep density and temperature gradient
- Separatrix between pedestal and SOL
- Neutrals and atomic physics
- Rapidly varying collisionality
- No clear separation between turbulent and MHD scale

Understanding of Turbulent Transport to form the Basis for a Reliable Predictive Capability in Externally Controlled Systems remains a Long-Term Goal





Electron thermal transport

- Observed electron thermal transport usually much larger than neoclassical level even with transport barrier
- Agreement between existing models and measurements is not as good as for ions
- Gyrokinetic simulations much more difficult because of shorter wavelengths

Particle transport

- Data from tokamaks demands both a diffusive and convective term to describe particle transport
- Neoclassical-like effects observed in particle transport

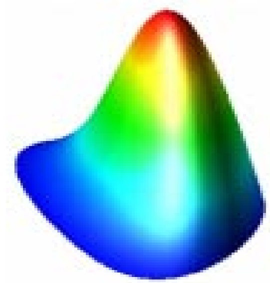
— Neoclassical pinch terms important especially in cases with reduced core thermal transport

Angular momentum transport

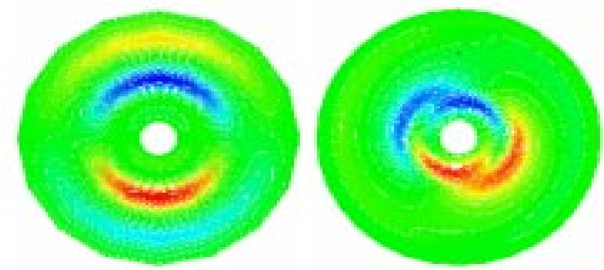
- Experimental angular momentum diffusivity in NBI plasmas similar in magnitude to ion thermal diffusivity
- Plasma rotation observed even when there is no apparent momentum input
- Experiments suggest some turbulent process is still transporting angular momentum even when it is not affecting ion thermal transport

Comprehensive Confinement Features are being modeled in Spherical Torus

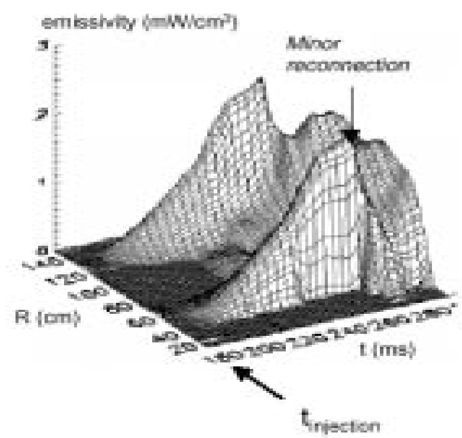
- **Sheared plasma flow included in equilibrium and stability calculations**
  - The growth rate with flow is reduced by a factor of three, consistent with the observed lack of sawteeth M3D
- **Extension and benchmarking of neoclassical and gyrokinetic theory to ST regimes**
  - Low ion transport observed in experiment supported by theory
  - GS2 calculations indicate short wavelength turbulent modes may dominate transport



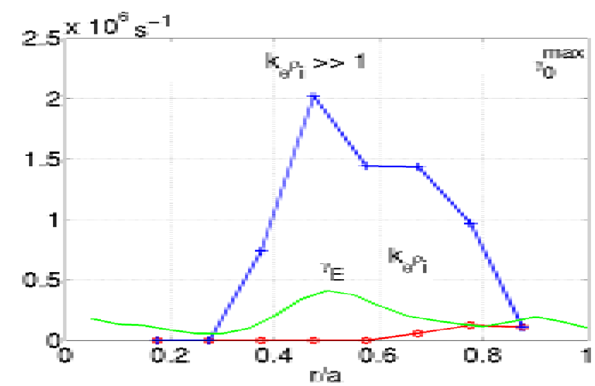
Toroidal velocity profile of 2D steady state



No Flow With Flow
MHD mode structure



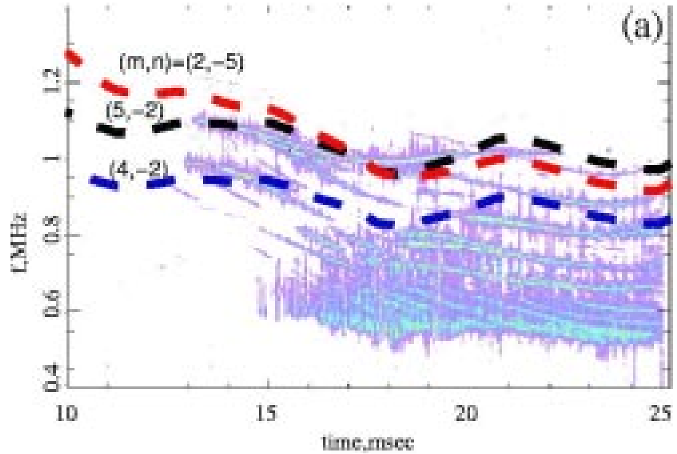
Neon puff exp'ts indicate almost no neon penetration to core



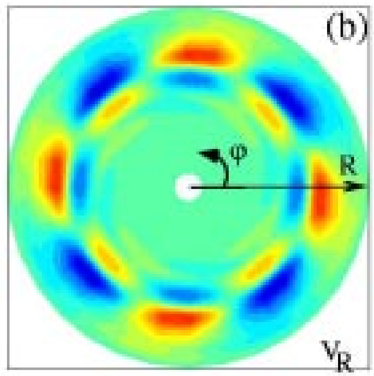
Linear growth rates and ExB shear damping rate

Spherical Torus offers an Opportunity for Studying Fast Ion Physics

- Develop understanding of self-consistent non-linear interaction of fast particles with MHD and implications for plasma heating and fast particle confinement
  - Confinement of fast particles in NSTX will contribute to understanding of α-confinement in burning plasma experiments, eg. ITER



Mirnov signal spectrum showing frequency peaks intersecting as the plasma equilibrium evolves. Theoretical predictions for the GAE dispersion for different (m,n) pairs $W=v_A(0)(m/q_0 - n)/R$ are shown as dashed lines



The results of HYM modeling of GAEs driven by fast beam ions are shown as a perturbed velocity of the background plasma. The possibility of plasma heating needs to be studied.

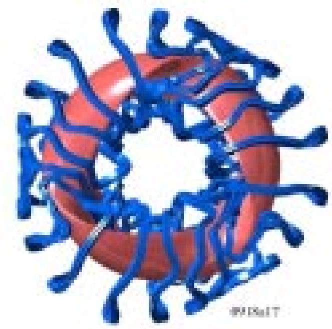
Incremental Funding Increase needed to solve the Fragmented Theory Support for the ST Program

High priority topics (with cross-cutting benefits to other confinement concepts)

- **Inclusion of toroidal and poloidal flow in stability analysis**
- **3-D modeling of CHI including current penetration and formation of closed flux surfaces**
- **Modeling power deposition, heating and non-inductive current drive using HHFW and EBW**
- **Assess implications of μ-turbulence and neoclassical transport theory for stochastic heating and heat pinches**
- **Understanding the role of diffusive and convective transport at the plasma edge**

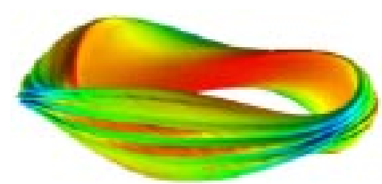
Extensive Equilibrium, Optimization and Stability Studies have been done on Compact Stellarators

- **3-D Equilibrium**
  - **VMEC: improved free boundary convergence, V3FIT reconstruction code**
  - **PIES: development of island diagnostics, island healing techniques**
- **Optimization**
  - **Comprehensive theory/physics-based optimization targets**
    - **transport, kink/vertical/ballooning stability, collisionless orbits, bootstrap consistency, island suppression**
  - **Two new compact configurations developed - unique role in world program**
    - **NCSX (quasi-axisymmetry), QPS (quasi-poloidal symmetry)**
- **MHD stability**
  - **Improved computational/analytical understanding of 3D ballooning**
  - **Resistive, two fluid and gyrokinetic energetic particle effects included in the M3D code and applied to evaluate energetic particle stability**
  - **NSTAB verified nonlinear stability on LHD, TRANSP modeling agrees with experimental confinement times**



NCSX flux surface and coils

QPS flux surface and coils



M3D ballooning mode in NCSX

Transport, Wave Heating and Edge Physics Studies have been initiated for 3-D Systems

Transport

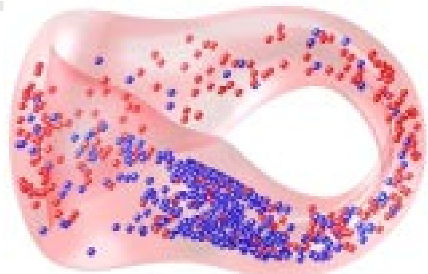
- Transport, plasma flow damping, and orbit confinement analysis predictions for the helically symmetric HSX system compared with experiment
- FULL code applied to study ITG, TEM modes
- Flexibility of QPS for studying transport evaluated

Wave Propagation and RF

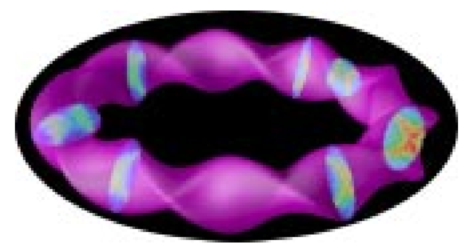
- 3D full wave RF calculations (AORSA) carried out for stellarator geometry
- Non-local wave-particle interactions formulated in conductivity operator

Edge Physics

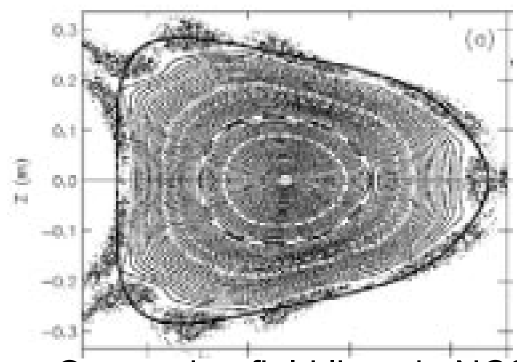
- Edge conditions are important to stellarator performance:
  - LHD improved dramatically with installation of carbon tiles
  - W7-AS: increased confinement time with divertor baffles
- UEDGE fluid neutrals model installed in BORIS (developed at IPP Greifswald)
- BOUT turbulence code algorithms upgraded to treat general 3D equilibria



Particle simulation of transport in QPS



AORSA 3D RF model of LHD

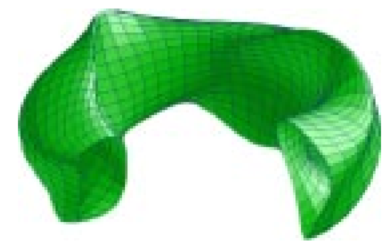


Open edge field lines in NCSX

A Number of New Critical Issues will need to be addressed for Helical Systems over the next few years (requiring additional funding)

Improve a critical set of MHD equilibrium and stability codes for the U.S. (and world) program (OFES FY2004 Performance Target)

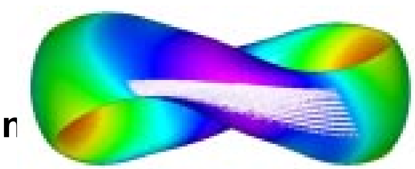
- **VMEC and PIES need improved convergence/efficiency**
- **Develop V3FIT flux reconstruction model (optimize location of magnetic diagnostics)**
- **Extend M3D to a free boundary model including neoclassical effects**



outer NCSX flux surface

Extend theories and codes to low collisionality

- **Radial drifts, high velocity space resolution of boundary layers**
- **Coupling to turbulence - viscous flow damping - momentum conservation**
- **Effects of broken magnetic surfaces on transport and flow shear**



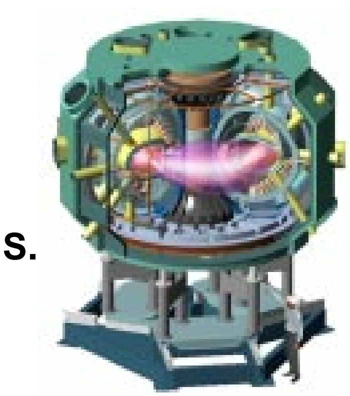
Collisionless trapped orbit In QPS

Develop improved 3 D boundary and divertor modeling

- **Analyze the edge transition region - nested surfaces change over to open field lines.**
- **Assess peak edge heat loads (ripple-trapped beam ions, ICRF tails, runaway electrons)**

Initiate transport and turbulent code development for 3 D systems

- **Presently there is no 3 D predictive or interpretive transport code in the U.S.**
- **Continue extension of BOUT turbulent code for 3 D equilibria**



NCSX device

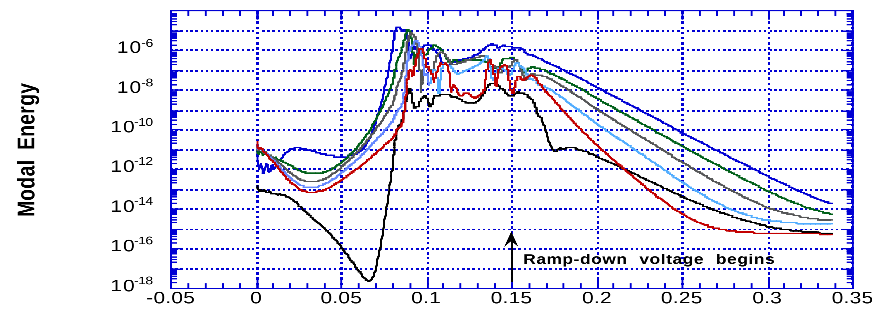
MHD Codes have Successfully Simulated Plasma Formation and Ramp-Down of ICC Configurations

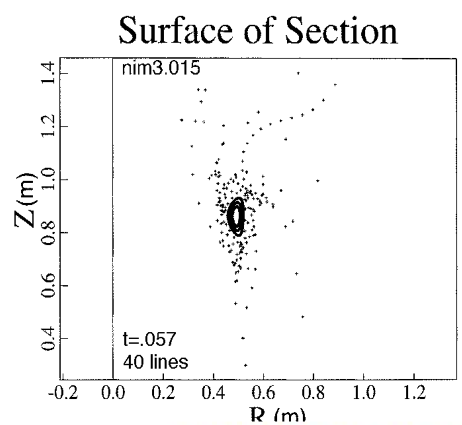
Stable ramp-down of Reversed-Field Pinches

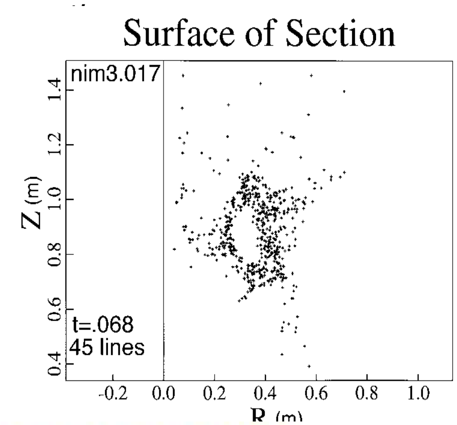
- Tearing mode stable self-similar decaying profiles exist with reasonable ramp-down rates.
- 3-D MHD simulations indicate these solutions are attractors.
- Unstable modes rapidly stabilized and decay

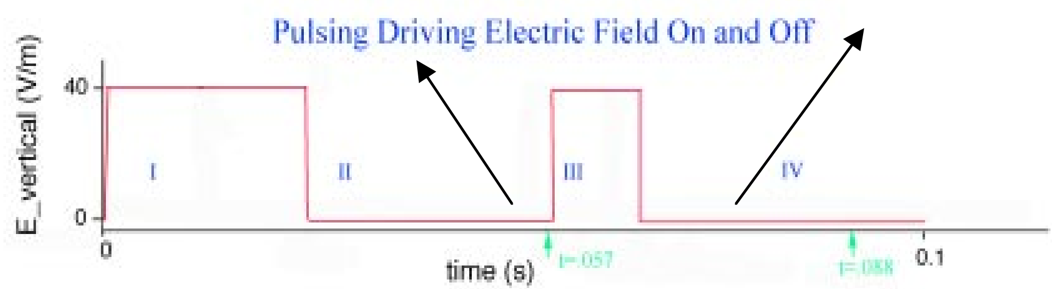
Growing closed flux in a spheromak (NIMROD)

- Helicity is injected with a driving E-field, n=1 mode excited & spheromak formed
- With driving field off, n=0 decays slowest & closed field lines formed
- With repeated pulsing, closed flux region can expand & magnetic energy can increase



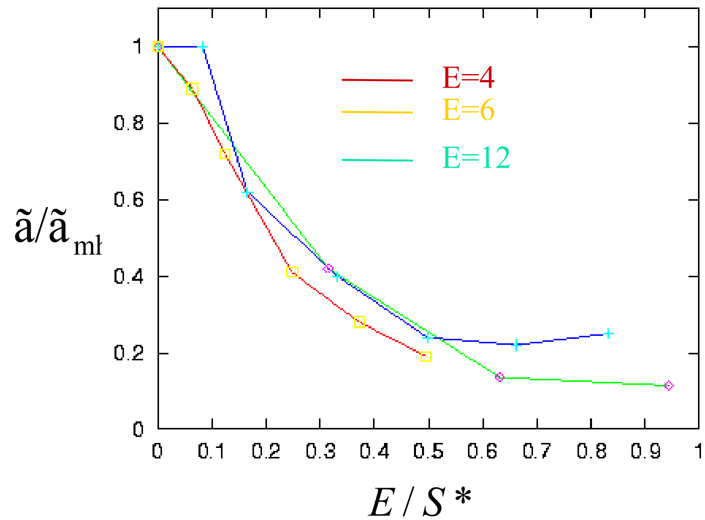




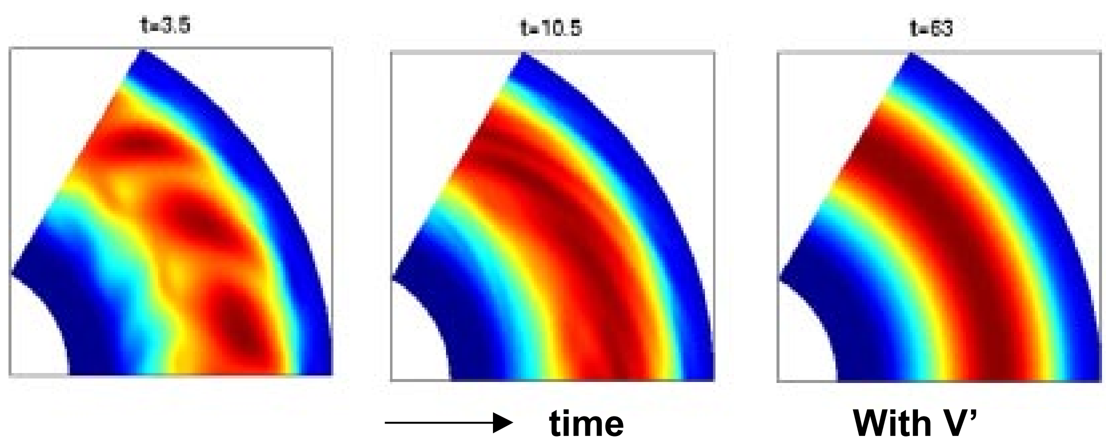


Good Progress in Understanding Stability of ICC Configurations

- **Hybrid simulation (HYM) has been developed to study the n=1 tilt instability in FRC**
  - **Demonstrated growth rate scaling with S^*/E**
  - **Resonant particle effects maintain instability at low S^***
  - **Scaling and nonlinear saturation agree with experiment**



- **3 D simulation of MCX (Maryland) shows centrifugal confinement**
  - **MHD stabilization of flute instabilities from velocity shear**



Theory Support for ICC's (especially Exploratory Concepts) is Spotty due to Sub-Critical Funding

Examples of Important Problems in ICC not being Addressed for Lack of Funds

- Electrostatic turbulence in RFP's
- Rotation effects on spheromak equilibrium + confinement
- Study of rotating magnetic field on FRC stability
- Collisional effects on FRC instabilities for MTF
- Convective cell formation and effect on transport in dipoles
- Study charge exchange, line radiation, and collisionless electron transport effects in centrifugally confined plasmas

Summary

- Tokamak theory and modeling are becoming increasingly sophisticated
  - Theory predictions lead experiments in many aspects
  - Increasing demand for code comparisons with experiments
  - Increasing demand for supporting ITPA activities
- ST theory addresses the needs of CDX-U, HIT-II, NSTX and PEGASUS
  - With increasing data, there is urgent need to extend theory to ST regime
  - Directly funded by OFES/NSTX ~ 6 FTEs, Theory/SciDAC ~ 2 FTEs; resources are fragmented (theorists working at ~ 0.1 FTE level per)
- The U.S. is the world leader in compact stellarator research
  - Theoretical tools are essential for design and construction of NCSX and QPS
  - Level of theory funding is ~ 10 FTEs; theory support for smaller experiments minimal
- ICC studies have made some impressive progress despite low level of funding
  - Understanding of magnetic turbulence in RFP is key to improved energy confinement
  - Strengthened theory support will be needed to move concept from CE to POP and beyond